NOTES AND UNIQUE PHENOMENA

DEVELOPMENT OF A RESISTANCE-BASED SENSOR FOR DETECTION OF WETNESS AT THE SOIL–AIR INTERFACE

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Abstract

Many microbes, including several fungal plant pathogens, often reside at or very near the soil surface. Survival, reproduction, and development of these pathogens are influenced by moisture in the environment. There are currently no efficient means to continuously monitor wetness conditions at the soil–air interface. A project was initiated to develop a sensor for continuous monitoring of soil–surface wetness and to be used in conjunction with data-logging equipment. Sensors were developed and tested for consistency and durability through replicate trials conducted on synthetic sponges and on thin soil layers. Field trials were then conducted to test sensor durability and response to field environments. Under greenhouse conditions, sensors were calibrated against tactile estimates of wetness on thin layers of three soil textures (sandy loam, clay loam, and silt loam) over a range of known moisture levels. In laboratory tests, sensors were evaluated for uniformity of response. Sensors were shown to be uniform in response under laboratory and field conditions. They worked well to indicate wetting events in the field and allowed for determination of wetness duration, a parameter of great interest to plant pathologists. The sensors, in conjunction with automatic data-logging devices, may be able to provide estimates of wetness duration for incorporation into disease predictive models.

Crop residue-borne fungi and other soil-surface–inhabiting microbes, including numerous plant pathogens, rely on water at or near the soil surface for survival, growth, and reproduction (Cook and Duniway, 1981; Griffin, 1972, 1978; Rotem, 1978). The water potential must be relatively high (in the range of –0.1 to –1500 kPa) for microorganisms to grow and reproduce although some species can withstand potentials as low as –20 000 kPa (Harris, 1981). The presence of moisture (i.e., wetness) at the soil–air interface or within the top few millimeters of soil is thought to be a very important factor in the development of certain plant pathogens and plant diseases (Cook and Papendick, 1972; Parry et al., 1995; Pfender et al., 1988; Swan et al., 2000; Yarwood, 1978; Zhang and Pfender, 1992). As an example, *Gibberella zeae* (Schw.:Fr.) Petch., a sporulating fungal pathogen and causal agent of Fusarium head blight in cereal crops (Dill Macky and Jones, 2000; Miller et al., 1998), will develop fruiting bodies (perithecia) and produce ascospores under favorable (i.e., high moisture) environments (Parry et al., 1995; Paulitz, 1996; Sutton, 1982). The ascospores are then available for delivery through the air to susceptible plant tissues. In other cases, residue-borne fungi will develop and become infective at the soil level, infecting root and crown tissues. Soil surface moisture, often associated with precipitation events or dew formation in the canopy (Rosenberg et al., 1983), is presumed to be one of the critical environmental factors affecting the development of these and other residue-borne pathogens (Rotem, 1978). Development of epidemiological models useful in plant disease forecasting often involves gathering data for many environmental parameters. The capacity to detect wetness at the soil–air interface and to estimate wetness duration would potentially aid current and future disease development models (Osborne and Jin, 2001). In certain situations, quantification of water at the soil surface may not be as important as classification of the soil surface condition as *wet* or *dry*, a qualitative classification whose definition is subjective and based on the requirements of individual applications. A practical application of this type of qualitative data is to determine *wetness duration* (based on time that the soil meets the predetermined wetness criteria), which can then be incorporated into models (e.g., pathogen/disease development predictions). Soil water is present as a dilute solution containing salts and other solutes and thus conducts electricity. This property of the soil solution allows for the use of conductance-based (or resistance-based) sensors in the soil environment.

Wetness at the soil–air interface has been difficult to estimate or measure with present technology. Gypsum (or Bouyoucos) soil moisture measurement blocks (Bouyoucos and Mick, 1940), tensiometers, neutron probes, time-domain reflectometry, and other tools have been used for estimating soil water parameters but are only suited for use at some depth below the surface. Electrical conductivity of the soil has been used to estimate soil wetness (Freeland, 1989; Hilhorst, 2000), but present instruments are used to estimate bulk soil wetness at some depth below the surface. Resistive, or conductance-based, wetness sensors have been used in a wide range of applications in agricultural research for many years. Small wire grids have been developed and used for direct estimation of surface wetness on leaves (Weiss et al., 1988), but those examined consisted of delicate wires and required very careful placement and would not be suited to the soil environment. Commercial wetness-sensing grids (e.g., Model 237, Campbell Scientific Inc., Logan, UT), which serve as artificial leaf surfaces in a plant canopy, are available for applications such as

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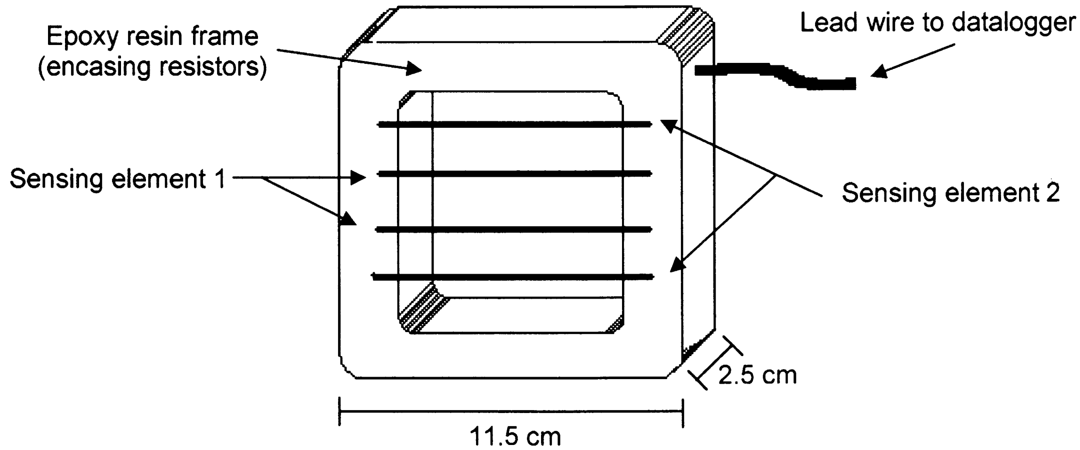

Fig. 1. Soil surface wetness sensor. The main components of the sensor are highlighted and include: two stainless steel wire sensing elements, the epoxy resin frame, and the lead wire for excitation and voltage measurement.

plant disease modeling (Gillespie and Kidd, 1978). The wetness-sensing grids are perhaps more durable than the delicate wire grid leaf wetness sensors mentioned above but consist of an opaque, solid surface beneath the sensing plane. If these sensors were used at the soil surface in direct contact with the soil, they would prevent free air and water movement to and from the soil surface, thus potentially over- or underestimating wetness duration. An effective soil–surface wetness sensor must be durable enough to be placed in contact with soil for long periods of time (e.g., growing season). The sensor should not fundamentally interfere with water evaporation from the soil or prevent precipitation from reaching the soil surface and should have negligible effect on the thermodynamics of the water at the soil surface (i.e., does not heat the soil or prevent appreciable heat loss). The objective of this study was to develop an instrument that would detect wetness at the soil–air interface. The instrument must also be able to provide measurements on short, regular intervals (e.g., every 30 min. for 60 d) without affecting the measured property, be compatible or adaptable to available data acquisition equipment, and be durable for use in field environments.

Materials and Methods

Sensor Construction and Operation

A sensor was constructed (Fig. 1) that consisted of a modified Wheatstone bridge circuit (i.e., half bridge) (Fig. 2) encased in epoxy resin (Por-A-Kast polyurethane resin kit, Synair Corp., Chattanooga, TN) with exposed stainless steel wires (sensing elements) for contacting the soil surface. The exposed wires in contact with variably conductive media (e.g., wet soil) create a variable resistor when a voltage is applied across the wires. Resistors at specific locations within the circuit allow for the indirect determination of the resistance across the two exposed sensing elements. The circuitry integrates two fixed resistors (R_1 = 1 kΩ and R_{100} = 100 kΩ) in series with the sensing elements (R_s = variable resistor). The fixed resistors are encased within the instrument frame. The exposed sensing elements consist of 14 gauge (1.63 mm) stainless steel wires. An AC excitation voltage (V_x) is applied to the instrument by an external source. In our case, a CR10X datalogger (Campbell Scientific Inc., Logan, UT) was used to apply a potential of 2.5 V. This excitation voltage (V_x) is then compared ratiometrically to a voltage (V_s) measured at a point in the circuit after resistor R_{100} and the sensor elements but before resistor R_1 (relative to the circuit flow). By Ohm's Law (voltage = current × resistance), assuming constant current, the ratio of these voltages (V_s/V_x) is equal to the ratio of R_1 to the sum of all resistors ($R_1 + R_{100} + R_s$), i.e., $V_s/V_x = R_1/(R_1 + R_{100} + R_s)$. To find the resistance across the sensor, the equation is solved for R_s, i.e., $R_s = [R_1(V_x/V_s)] - (R_1 + R_{100})$. For example: If the voltage measured at V_s = 0.01 V, the resistance (R_s) = [1 kΩ(2.5 V/0.1 V)] – 101 kΩ, or 149 kΩ resistance across the sensing elements. When there is no conductance (or conductive media) between the sensing elements, the circuit is open, and resistance (R_s) is infinite. When water is present in the soil solution, the solution electrolytically completes the circuit, and resistance across the sensing elements can then be determined. (Solutes are assumed to be present in the soil solution at a concentration sufficient to conduct electricity.) Resistance is higher when moisture levels are low and approaches a minimum when free water is present.

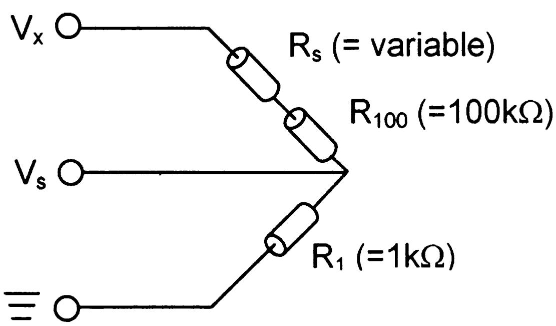

Fig. 2. Half-bridge circuit diagram. V_x = excitation voltage, V_s = measured voltage, R_s = variable resistance across the plane of sensing elements (i.e., sensor resistance), and R_1 and R_{100} represent integrated fixed resistors.

Initial Sensor Testing

Initial testing was conducted using five sensors. Each sensor was placed on an absorbent, synthetic sponge. Sensing elements were held in contact with the sponge using rubber bands to prevent movement of the sensor. The sponge and sensor were placed 25 to 30 cm beneath an incandescent lamp (150 W) to hasten evaporation. Measurements were recorded by a CR10X datalogger. Several (5–10) measurement cycles (30-s intervals) were allowed to elapse with the sensor in contact with a dry sponge to ensure that an open circuit was present. Tap water was then added to saturate the sponge, and readings

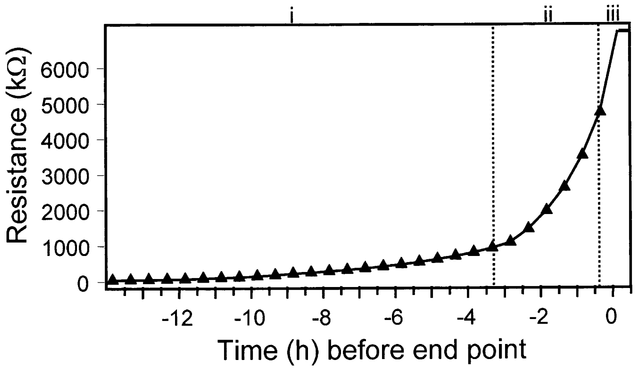

Fig. 3. Sensor output from sponge trial. End point is defined as 6999 kΩ resistance (very dry substrate, limit of measurement, indication of overrange by CR10X). Three curve segments are designated by lowercase roman numerals (i, ii, iii) as discussed in the text.

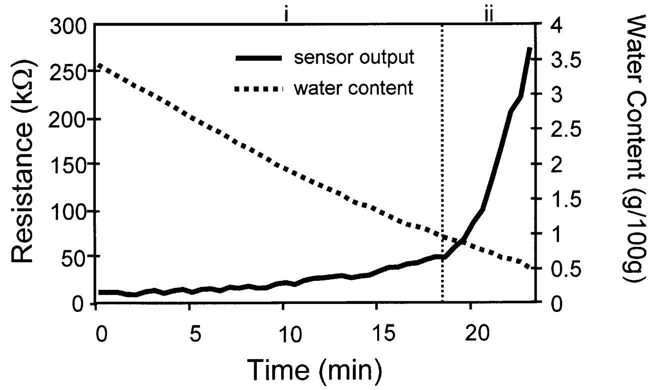

Fig. 4. Sensor output and water content over time on a thin soil layer. Two curve segments are designated by lowercase roman numerals (i, ii) as discussed in the text.

were obtained every 5 min until the sponge was very dry to the touch. Three repetitions of this procedure were conducted for each sensor. The end point of the drying was determined to have occurred when an open circuit was first detected (overrange reading by the CR10X datalogger, 6999 kΩ). The end point for each curve generated by the procedure outlined above was used to compare data sets. Each end point was considered to be time zero ($T = 0$), with preceding data recorded as time before end point. Data were reduced by selecting points at each half hour (−30, −60, −90 min…) before the end point, for a period of 12 h, resulting in 24 data points per trial. A pooled analysis of variance for measurements over time (JMP, 2001) was performed. Figure 3 is an example of the sensor output after data reduction.

Further testing was performed on seven of the sensors using a thin layer of soil as the substrate. Air-dry field soil (Vienna silt loam, a fine-loamy, mixed, superactive, frigid Calcic Hapludoll) was screened to pass a 2-mm sieve, and 100 g was placed into a square plastic sandwich box to form a layer of soil approximately 4 mm in depth. Individual sensors were placed atop the soil layer, with the sensing elements embedded slightly (1–2 mm), and then secured with rubber bands. The entire assembly was placed on a digital balance. The balance was zeroed, and the soil was carefully and evenly wetted using a trigger-pump misting sprayer to apply 12 g of tap water to the measurement zone only. The system was allowed to set undisturbed for 15 to 20 min to allow for water absorption. The resistance across the sensor and the weight of water remaining were recorded until an open circuit was indicated. This procedure was repeated three times for each sensor. A natural log transformation of the resistance values was performed to improve linearity. A regression equation was derived for each curve, and the slopes were entered into an analysis of variance (JMP, 2001) to determine uniformity of response.

Calibration of Sensors

Each sensor was calibrated on three soil textures (sandy loam, silt loam, and clay loam as determined by particle size analysis) from undetermined sources in thin-layer trials. Organic matter, pH, and electrical conductivity analyses were performed on the soils. Soils used had low organic matter content (<1%), were slightly basic (pH 7.3 to 7.9), and had low electrical conductivity (0.04 to 0.06 S m^{-1}). For each soil texture, a range of six gravimetric moisture contents (2, 4, 6, 8, 10, and 12% water) were established as thin soil layers in steel pans. Soil moisture levels were established by adding predetermined amounts of water to 300 g of oven-dry soil followed by thorough mixing. Water lost to evaporation was replenished as needed every 6 to 10 min by weighing each pan and misting the soil until the desired weight was re-established. Generally, very little water (less than 0.5 g) was lost during each interval. Calibrations were conducted against both the gravimetric moisture content of the soil as well as tactile estimates of surface wetness. Soils were classified as *wet* or *dry* based on appearance as well as tactile estimates, which were performed by gently contacting the soil with dry, bare skin of the fingers. Soils were deemed to be wet if the surface felt damp to the touch and appeared darker than an oven-dry check pan of the same soil type. When the soil surface appeared as variously dark and light and was accompanied by supporting tactile estimation, the surface was considered to be wet. Sandy loam was always determined to be wet at the 4% moisture level and above. Silt loam and clay loam soils were determined to be wet at 6% moisture and above. Sensors were placed onto an arbitrarily selected pan, allowed 10 s to settle, and then a resistance measurement (kΩ) was recorded, after which the sensor was moved to a different pan. Each moisture level for a given soil type was measured 12 times with each sensor. Data were analyzed using means comparison (JMP, 2001) to determine if adjacent moisture levels resulted in significantly different resistant measurements.

Field Trials

For field testing, sensors were incorporated into an existing CR10X-based weather monitoring system within research plots at Brookings, SD, in years 2000 (SD00), 2001 (SD01), and 2002 (SD02). Additional testing was conducted at sites in 2001 and 2002 near West Lafayette, IN (IN01, IN02); Fargo, ND (ND01); Wooster, OH (OH01a); and Hoytville, OH (OH01b). Each location received three sensors for testing. Soil(s) at locations SD00, SD01, and SD02 were Vienna silt loam; IN01 and IN02 were Raub silt loam (fine-silty, mixed,

Table 1. Means comparison for output [ln(resistance)] of 28 sensors at specific water content as part of thin soil layer calibration on three soil textures.

	Soil texture		
Water content	Sandy loam	Silt loam	Clay loam
%	ln(kΩ)		
2	3.84	6.28	6.82
4	2.53	3.91	5.02
6	1.68	3.13	3.79
8	1.50	2.38	2.89
10	0.82	2.40	2.23
12	0.22	1.58	1.36
LSD (α = 0.05)	0.74	0.38	0.53

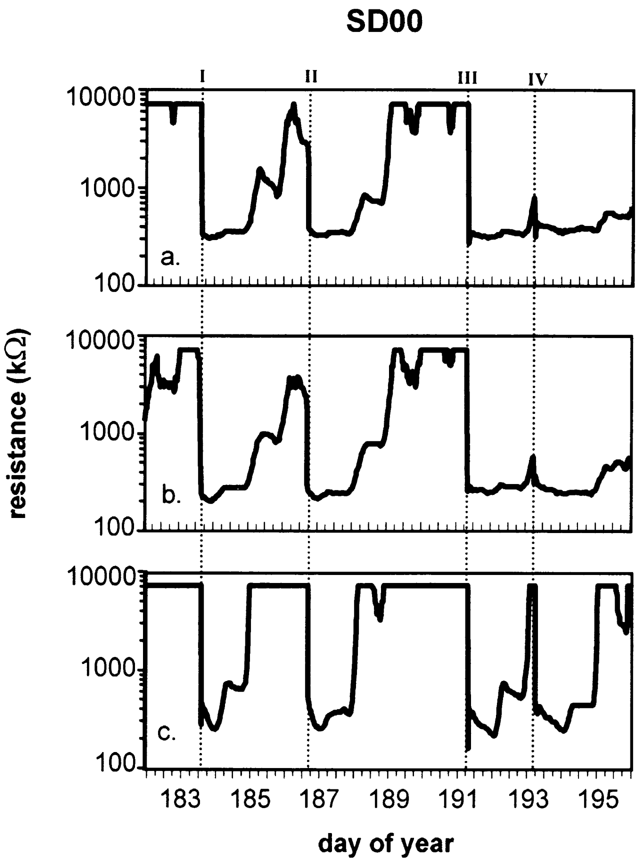

Fig. 5. Output (resistance) over time for three soil wetness sensors from the South Dakota location in 2000 (SD00). Dotted lines and roman numerals indicate precipitation events (I = 5.3, II = 5.3, III = 9.1, and IV = 16.0 mm). This location-year was characterized by large, infrequent rain events with drying conditions in the interim periods. Soil was Vienna silt loam.

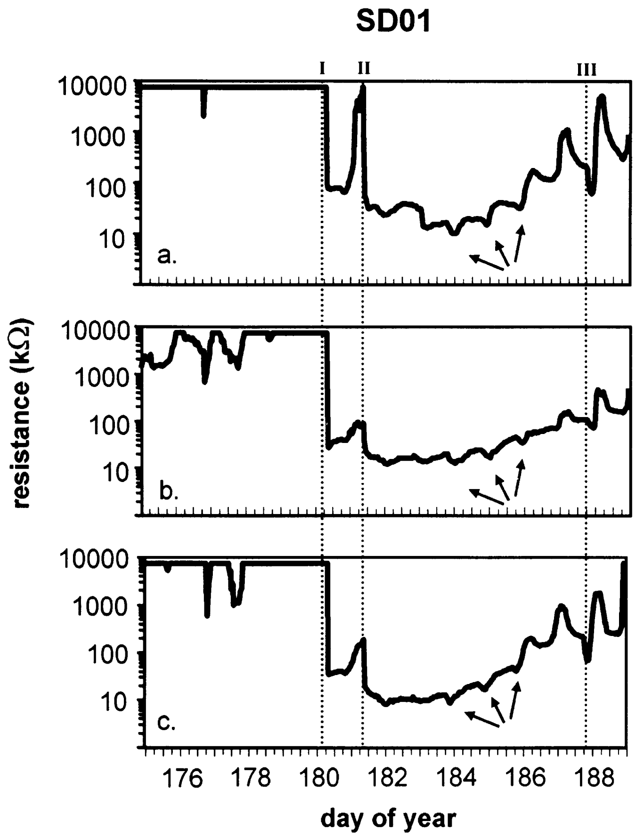

Fig. 6. Output (resistance) over time for three soil wetness sensors from the South Dakota location in 2001 (SD01). Dotted lines and roman numerals indicate precipitation events (I = 4.1, II = 14.7, and III = 0.3 mm). This location-year was characterized by few large, infrequent rain events with variable conditions in the interim periods. Arrows on the figures are indicating examples of day-to-day fluctuations in sensor output during prolonged wet conditions (can be seen for other locations as well). Soil was Vienna silt loam.

superactive, mesic Aquic Argiudolls); ND01 was Fargo silty clay (fine-montmorilloritic, frigid Vertic Haplaquoll); OH01a was Wooster silt loam (fine-loamy, mixed, mesic Oxyaquic Fragiudalfs); and OH01b was Hoytville silty clay loam (fine, illitic, mesic, Mollic Epiaqualfs). Sensors were evaluated for durability and reliability under field conditions based on sensor physical condition following each field trial and consistent response to wetting events. Sensors were in place for periods ranging from 3 wk to 2 mo. Locations SD00, SD01, SD02, and ND01-1 were planted to spring wheat (*Triticum aestivum* L.) following disc tillage. Locations IN01, IN02, OH01a, and OH01b were planted to winter wheat following moldboard plowing plus disc tillage. Environmental parameters measured at each site included air temperature, relative humidity, solar radiation, wind, precipitation, and leaf wetness. Soil temperature was monitored at some locations.

For each sensor, a 12- by 12-cm area was cleared of plant residues and large (>1 cm), loose soil aggregates, and the surface was leveled to provide an even contact area for sensor elements. A light, even pressure was applied to the units to embed the sensor wires into the soil up to the thickness of the wire (1 to 1.5 mm). Sensors were checked often for proper placement and to ensure they were unobstructed by debris.

Soil surface wetness measurements and other weather data were collected at all sites every 30 min for the duration of each field trial. As no direct, quantitative verification of sensor performance was available, soil wetness sensor readings were compared anecdotally to weather parameters such as radiation, humidity, and precipitation. A precipitation event, for example, should precede an indication of transition from dry to wet (assuming the surface was dry before precipitation). High radiation and temperature, with low relative humidity, should result in rapid drying of the surface. Soil wetness sensor measurements at a given time were also compared with the other soil wetness sensors for that location to determine the uniformity of response to wetting events or for potential errors.

Results and Discussion

Sensor Development and Initial Testing

In both the sponge and thin soil layer trials, sensor measurements resulted in the response curves represented by Fig. 3 and 4 when plotted against time (or against water loss). In the figures, important segments are designated by roman numerals (i, ii…). The first segment (i) of the curve indicates a stable or slight increase in resistance (over time, or with evaporation) as the substrate dries. This is likely due to the movement of water out of the macropores initially, which would leave most of the micropores filled (or partially filled) to allow conductance. Also, it was assumed that solute concentration in the remaining solution increased with

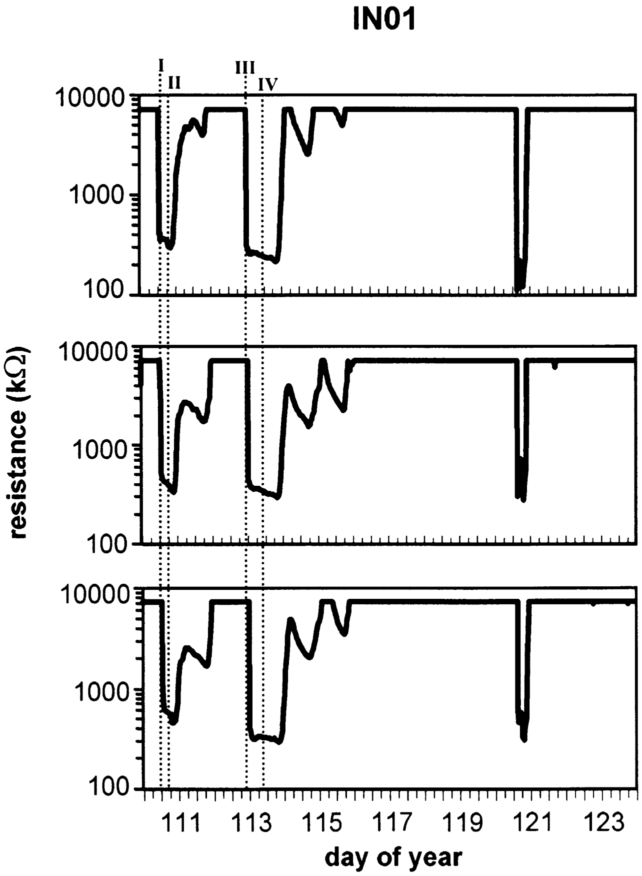

Fig. 7. Output (resistance) over time for three soil wetness sensors from the Indiana location in 2001 (IN01). Dotted lines and roman numerals indicate precipitation events (I = 1.8, II = 0.8, III = 3.3, and IV = 1.78 mm). This location-year was characterized by small rain events concentrated within a relatively short time period, followed by dry conditions thereafter. Note the large fluctuation on day 121 with no rain event. This response is thought to be a result of heavy dew within the canopy and on the soil surface. Soil was Raub silt loam.

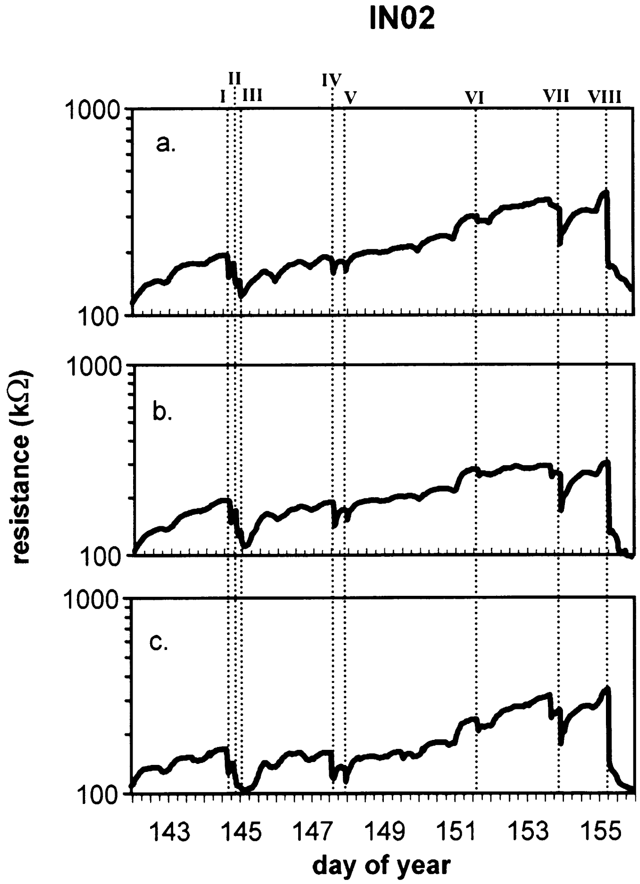

Fig. 8. Output (resistance) over time for three soil wetness sensors from the Indiana location in 2002 (IN02). Dotted lines and roman numerals indicate precipitation events (I = 1.0, II = 1.3, III = 5.8, IV = 0.8, V = 0.3, VI = 0.3, VII = 1.5, and VIII = 33.5 mm). This location-year was characterized by several small rain events, spaced sporadically, with damp conditions in the interim periods. Soil was Raub silt loam.

evaporation of water and therefore potentially increased the electrical conductivity of the solution, thereby compensating for the loss of conductive area. The second segment of the curve (ii) was designated the transition segment. The sensor output began to rise at an exponential rate over time (or with evaporation). It is assumed that as the substrate dried, fewer and fewer pores remained electrolytically conductive due to loss of water (and continuity), which would result in increased resistance as measured by the sensor. During this phase, the soil surface appeared to be mottled light and dark as compared with the oven-dry reference soil. In the sponge trials, the surface felt wet throughout the first phase of the curve. The second phase initially felt wet to the touch but, over time, transitioned to dryness. The final portion of the curve (iii) in Fig. 3 is described as the *dry response*. (This third portion of the curve is not shown in Fig. 4.) The sensor resistance increased from large, but measurable values to beyond the range of the datalogger, essentially an open circuit. Visually, the soil appeared to be light in color, similar to the oven-dry reference.

The transition period was variable, depending on substrate characteristics. The transition period for sensors on sponges lasted much longer than on the thin soil layers. Sandy soil, with a, overall larger mean particle size than clay for example, would dry more rapidly and allow breaks in electrical continuity, resulting in a more rapid transition from wet response to dry response. The stable resistance value (i.e., the first phase of the response as outlined above) for a wet substrate would presumably vary more in response to such soil characteristics as soluble salt content and other chemical properties than to textural differences alone. This variability in substrate characteristics and sensor response indicates the need to calibrate sensors under specific environments as necessary to determine the resistance values indicative of wet or dry surface conditions.

Analysis of the sponge trial data showed that all sensors responded in a statistically similar manner to drying. The analysis suggests that measurements would be fairly consistent across sensors on the same substrate. For individual sensors, the response curves were consistent over replications in the sponge trials, suggesting consistency of response of individual sensors when subjected to similar wetting/drying conditions. In thin soil layer

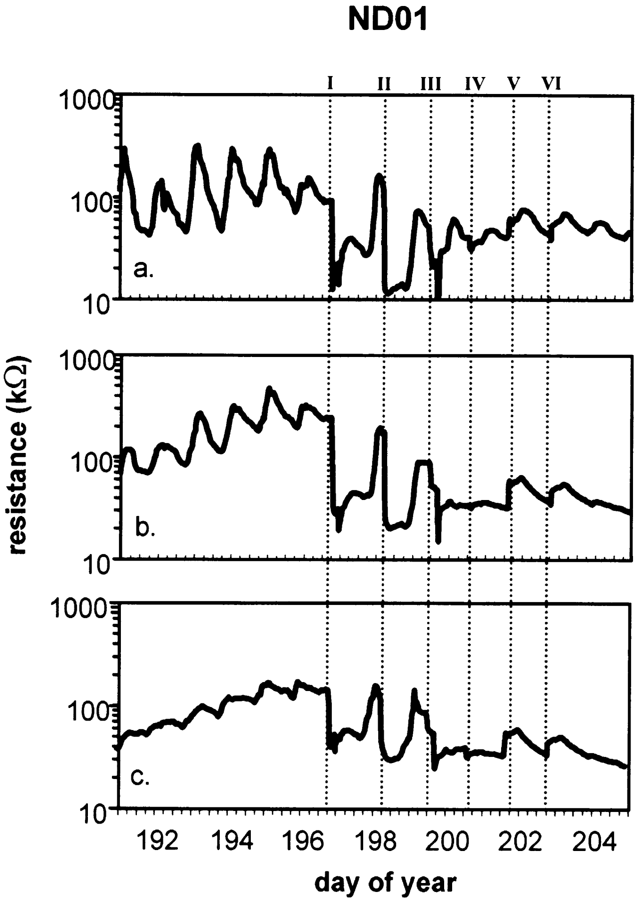

Fig. 9. Output (resistance) over time for three soil wetness sensors from the North Dakota location in 2000 (ND01). Dotted lines and roman numerals indicate precipitation events (I = 1.0, II = 0.8, III = 5.1, IV = 3.3, V = 14.5, and VI = 14.5 mm). This location-year was characterized by wet conditions, with regular rain events of varying intensity and variable conditions in the interim periods. Soil was Fargo silty clay.

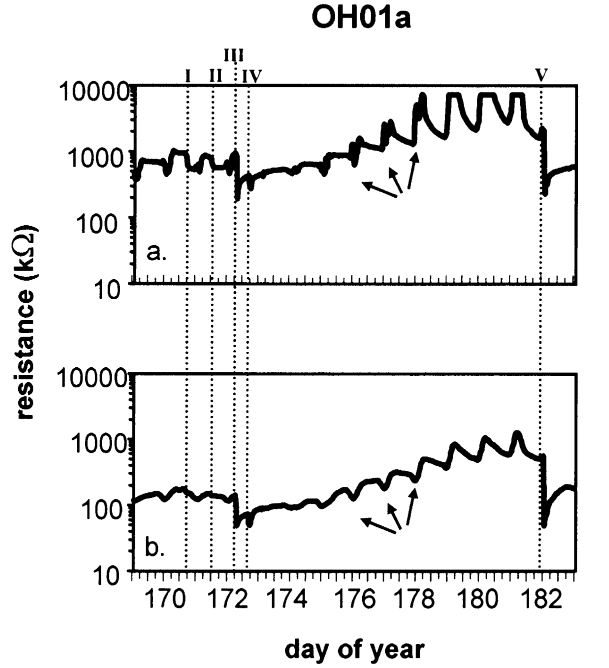

Fig. 10. Output (resistance) over time for two soil wetness sensors from Wooster, OH, location in 2001 (OH01a). Dotted lines and roman numerals indicate precipitation events (I = 0.5, II = 0.5, III = 3.3, IV = 2.8, and V = 12.7 mm). This location-year was characterized by several variable-intensity rain events concentrated in a short time period, with moderately dry conditions thereafter. Arrows indicate day-to-day fluctuations in sensor output during prolonged wet conditions. Soil was Wooster silt loam.

trials, sensor response was more variable over repetitions than in sponge trials. The slopes of the resistance by water loss curves for sensor response in thin soil layer trials were analyzed and were not found to be significantly different, again indicating consistency over replication and uniformity across numerous sensors.

Calibration

Each sensor was calibrated against gravimetric moisture as described above. Variability in sensor response was lowest at 8 to 12% water contents and highest at the 4 and 6% water contents. The variability in sensor output on the dryer soils is attributed to slight differences in the water distribution in the apparatus, as well as the variation in placement of the sensor with each measurement. Calibration values for individual sensors were determined using Eq. [1] (for clay and silt loam soils) or Eq. [2] (for sandy loam soil), where $R_{2\%}$, $R_{4\%}$, and $R_{6\%}$ represent mean sensor output at 2, 4, and 6% water content, respectively:

$$\text{wet/dry boundary (clay and silt loam)} = \exp[(\ln R_{4\%} + \ln R_{6\%})/2] \quad [1]$$

$$\text{wet/dry boundary (sand loam)} = \exp[(\ln R_{2\%} + \ln R_{4\%})/2] \quad [2]$$

Calibration values served to indicate the break point between wet and dry conditions and ranged from 40 to 300 kΩ for the 28 sensors and three soils used in this study. The variation in values was likely due (apart from variation due to soil type) to slight differences in component resistors, soldering, sensing elements, lead length, sensor age, or other construction variations. The means comparison analysis (Table 1) for all sensor calibration data shows that there was significant difference ($P < 0.01$) among means for sensor output at different water content levels on a given soil type.

Field Testing

Field test results are presented in Fig. 5 through 11. Data from one of three sensors at the OH01 location and from all three sensors at the SD02 location were discarded due to errors in the data collection and processing. This set of figures is intended to show the uniformity of sensor response by all sensors at a given location. Sensor response to wetting events was very rapid in all cases, unless soil was very wet at the time of the wetting event. Sensor response to drying was typically much slower and resembled the initial tests of sensor performance with some notable exceptions. Small day-to-day cyclic fluctuations in the sensor response are evident at all locations but are particularly evident in Fig. 6 and 10 (SD01 and OH01-1, respectively), and examples are

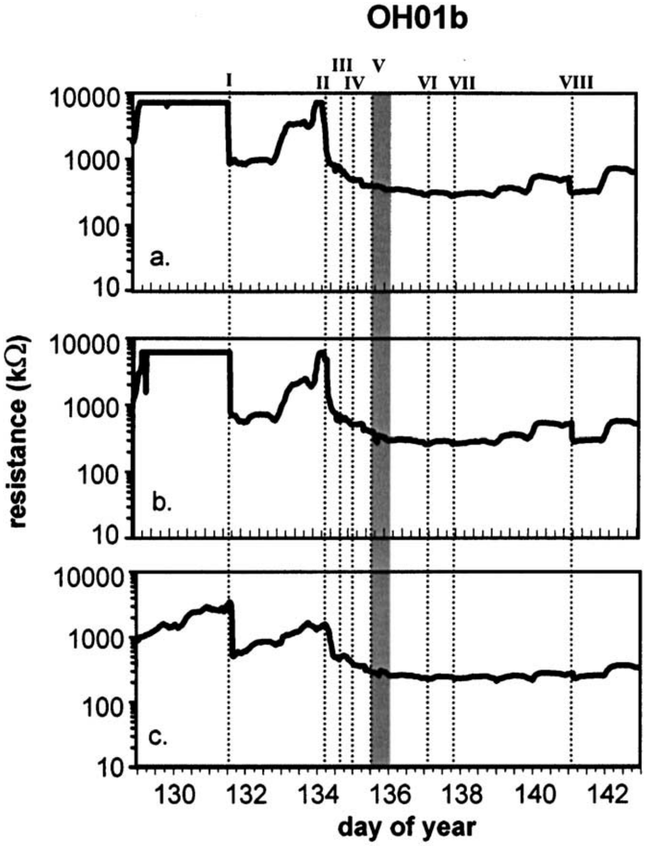

Fig. 11. Output (resistance) over time for three soil wetness sensors from Hoytville, OH, location in 2001 (OH01b). Dotted lines and Roman numerals indicate precipitation events (I = 9.4, II = 1.8, III = 24.9, IV = 0.5, V = 29.2, VI = 0.8, VII = 2.5, and VIII = 2.0 mm). This location-year was characterized by many variable-intensity rain events, some of which were of long duration (event V = 13 h, indicated by shaded area), with damp conditions in the interim periods. Soil was Hoytville silty clay loam.

indicated on those figures. During wet conditions, the fluctuating values tended to reach a maximum between midnight and 0600 h and a minimum during midday. This trend was reversed during dry conditions when fluctuating values peaked at midday and were minimal in the late night to early morning hours. The fluctuations observed during dry conditions were attributed to a slight increase in water content of the soil surface in the early morning hours, perhaps due to condensation or dew. For example, during day 121 at location IN01, a steep reduction in resistance followed by a sharp rise was observed; however, no precipitation event was recorded during that time. Examination of the temperature and humidity measurements made concurrently suggested that very heavy dew was likely during that time period and perhaps resulted in a short-term wetting of the soil surface.

The soil surface wetness sensors performed well in all laboratory and field trials. The sensor was durable for at least two crop seasons in the field. Results of the field tests showed that the sensor responded rapidly to wetting events and drying conditions. The data from this sensor should be useful in generating soil wetness duration data and allow for the inclusion of duration data in plant disease modeling applications. Freeland (1989) reviewed the use of resistive sensors for estimation of soil moisture and determined that there was much skepticism about their use due to calibration concerns. The need for calibration of individual sensors was demonstrated in this study. Temperature fluctuations and variability in soil characteristics tend to increase the sensor variability, and it is recommended that sensors be calibrated for specific applications to determine threshold levels for wetness determination. The potential applications for this type of sensor include plant pathogen modeling, soil microbiological studies, residue monitoring, plant disease epidemiological studies, soil physics research, cropping systems management studies, and others.

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